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Making sense of cosmic-ray soil moisture measurements and eddy covariance data with regard to crop water use and field water balance

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ABSTRACT

Changes in soil moisture influence the water availability to crop plants and soil ecological processes like carbon and nutrient cycling, impacting on crop productivity and environmental performance (greenhouse gas emissions, leaching) of agricultural systems. While traditional soil moisture measurements are done using point-based methods, the recent development of the cosmic-ray soil moisture neutron sensor (CRNS) offers the opportunity to measure soil water at the field scale. However, due to its shallow (< 300 mm) and variable measurement depth, the relevance of the measurements to crop water use has been questioned. In this paper, we combine point-based soil moisture measurements (soil cores, TDR), areal-based soil moisture and evapotranspiration measurements (CRNS, eddy covariance), and soil-plant systems modelling together to investigate the consistency in measured soil moisture and crop water use with these different methods We also quantify how relevant the CRNS soil moisture measurements are in understanding the water use of cereal crops (wheat and barley). Our results show that crop water uptake from CRNS layers accounted for 50–90% of the total water uptake in dry environments (location, year) with annual rainfall < 300 mm, but only 30–50% of the total crop water uptake in wetter environments (locations, years). This demonstrates a higher relevance of CRNS measurements in semi-arid and arid regions where water is a limiting factor for crop growth and other ecological processes. The high temporal resolution of soil moisture data from CRNS can be assimilated with eddy covariance measurements and point measurements in field to better calibrate soil-plant models and to more accurately simulate field water balance.

1. Introduction

Soil moisture dynamics and field water balance affect crop growth, grain yield and other ecological processes like salinity, nutrient transformation, and emission of greenhouse gases (GHGs; N_2O, CO_2, CH_4) from soil. Most current environmental problems that occur in agricultural areas arise from altering the dynamics of the agricultural water balance without an understanding of the long term response of the system. For example, salinization is associated with changes in the surface water balance induced by removal of native grassland and clearing of deep rooted native vegetation. These changes increase groundwater recharge, which in turn leads to rising water-tables and salinization (Zhang and Walker, 2002). Other examples include the impact of altered soil moisture dynamics on emission of GHGs from soil (Xing et al., 2011; Thorburn et al., 2010). Short term agronomic studies alone cannot identify optimal or appropriate land use or management practices to address the changes that occur over long periods. The problem can be addressed by combining well instrumented field experiments and system models (Van Dijk, 2011). In that regard, continuous and reliable measurements of profile soil water, and the other terms in the water balance (evaporation, crop transpiration, runoff, drainage) are the key to understanding the processes and validation of process-based models.

Traditionally, most ground based measurements of soil water content (SWC, cm^3/cm^3) are made at a 'point'. The methods used vary from core samples (gravimetric or volumetric), time domain reflectrometry (TDR) or capacitance probes or neutron probes. Because of the spatial heterogeneity present in SWC, it is often difficult to determine the average value for large agricultural fields, although time-consuming replicates of measurements can be made at different points in a field. The cosmic-ray neutron sensor for measuring soil water content (CRNS; Zreda et al., 2012, Franz et al., 2012) offers the opportunity to measure

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soil water at the field scale (5–28 ha) for depths from 100 to 850 mm, depending on SWC (McJannet et al., 2014; Hawdon et al., 2014; Bogena et al., 2013; Köhli et al., 2015). Efforts have been made to use such measurements for estimating field-scale SWC and crop water use (Avery et al., 2016; Foolad et al., 2017). However, due to the shallow and variable measurement depth of the CRNS (Peterson et al., 2016), and the much deeper water extraction of crop root systems (particularly in semi-arid and arid areas; Verburg and Bond, 2003), the relevance of the measurements with regard to crop water use has been questioned.

The eddy covariance provides a direct measure of the net exchange of carbon dioxide and water vapour across the canopy-atmosphere interface over an area (Meyers and Baldocchi 2005; Baldocchi 2003). The area sampled has a longitudinal upwind dimension in the order of a hundred meters. The method is most applicable to flat terrain, when the environmental conditions are steady, and the underlying vegetation extends upwind for an extended distance (Baldocchi 2003). It provides an average flux from an area, minimising the point scale variations (Harper 2005). The successful application requires the use of large experimental areas (Harper 2005; Baldocchi 2003). Placing the measurement equipment in the middle of the area provide a long fetch, in the order 100 m, irrespective of the wind direction. Meyers and Baldocchi (2005) discuss the assumptions and uncertainties underlying the eddy covariance technique.

Whilst numerous studies have combined point-based measurements and soil-plant systems modelling (e.g. Agricultural Production Systems sIMulator to study field water balance, crop water use and other processes (Chen et al., 2011; Archontoulis et al., 2014; Gaydon et al., 2017), fewer studies (Verburg and Bond 2003; Dolling et al., 2005) have evaluated model against areal-based SWC (e.g. comic-ray probe) and evapo-transpiration (Et; e.g. eddy covariance method) measurements. How the point-based measurements compare to those areal measurements remains less known.

The aim of the paper is to combine field measurements and process-based soil-plant modelling to quantify: 1) the consistency of SWC measured with two point-based methods (soil cores, and TDR) with those measured with the area-based cosmic-ray neutron sensor (CRNS), 2) the consistency of evapotranspiration determined by field water balance with point-based soil core data and measured using area-based eddy covariance approach, 3) the performance of APSIM in simulation of soil moisture dynamics, evapotranspiration and crop water use, and 4) the relevance of CRNS soil moisture measurements to crop water use across different climatic regions.

2. Material and methods

2.1. Study site and field experiment

The field experiment was performed over 2 years (2013–14) in an Australian cereal field, ca. 30 ha area (530 m by 560 m) at Temora in New South Wales (Lat: −34.4061; Long: 147.5248; Fig. 1). The soil in the experimental field is a Red Chromosol (Isbell, 1996), close to a soil site with the profile number Temora No 913 in the APSoil database (https://www.apsim.info/Products/APSoil.aspx). Specific measurements of bulk density, organic carbon, pH, and clay content within the experimental field were used to derive the soil profile characterisation and to parameterise APSIM. Plant available water capacity (PAWC) was estimated to be 167 mm in the upper 1 m of soil and 206 mm to a depth of 1.6 m (Table 1). Details on how to estimate PAWC are given in the APSIM parameterisation section.

The experimental site has an average maximum temperature (2000–2016) of 34 °C in January and average minimum of 2.6 °C in August. The average annual rainfall is 470 mm, with a minimum of 197 and a maximum of 747 mm. Rainfall in 2013 and 2014 was 403 and 499 mm, respectively. Daily metrological data for the site are available from Queensland Government Department of Science, Information Technology and Innovation (DSITI; https://data.qld.gov.au/dataset/silo-patched-point-datasets-for-queensland) and Australian Bureau of Meteorology.

The crop sequences were wheat (2013), summer fallow and barley (2014). Wheat (cultivar Gregory) was sown on 14 May 2013, top dressed with 200 kg/ha of urea (equivalent to 92 kg N/ha) on 6 August and harvested on 18 November 2013. Barley (cultivar Scope) was sown on 14 May 2014, top dressed with 217 kg/ha of urea (equivalent 99.8 kg N/ha) and was harvested on 10 November 2014. The stubble of the crops were left standing and grazed by sheep during the summer.

2.2. Record of onsite rainfall

Rainfall data include 30 min data measured by the rain gauge mounted on the Eddy Covariance system and hourly measurement from the rain gauge together with the cosmic-ray probe (CRNS). Gaps in the data were in-filled by combining both data sources and these site specific rainfall data were used for the simulation. In summary, 263 mm of rain (P) was recorded from 2 May 2013 to the end of the wheat growing season, with 22 mm falling on 16 November 2013 when the wheat was mature. A total of 135 mm was recorded during the fallow period (Nov – 1 April 2013) and 274 mm during the barley growing season. The periods selected to do the cumulative sums do not match exactly to the growing season. Rather, the start and end dates were selected to match the soil coring at the beginning of each phase.

2.3. Crop measurements

Crop measurements were made by cutting 5 adjacent rows, 0.39 m long (0.483 m^2) at growth stages Z31 (6 August 2013–wheat; Zadoks et al., 1974; Tottman 1987), Z37 (29 August 2013), Z75-76 (10 October 2013) and maturity (18 November 2013). Barely was sampled by cutting 4 adjacent rows 0.5 m long at Z32 (14 August 2014), Z65 (anthesis – 24 September 2014) and harvest ripe (7 November 2014). The samples were weighed fresh, and subsamples (approximately 50 stems) separated into components of leaves, sensed leaves, stem, head and grain. The components from the subsamples were dried at 70 °C until a constant weight was achieved, ground and analysed for total N by combustion (C&N analyser). Grain yields were also measured by hand harvesting large areas ($> 1.0\,m^2$) of crop and threshing. This allowed total dry matter production, harvest index and residue to be determined.

2.4. Soil measurements

Nine soil cores (45 mm internal diameter) were collected randomly from the field to measure SWC, ammonium (NH_4-N), and nitrate (NO_3-N) contents in the 0–1.9 m soil layers. Mineral N data is not reported in this paper. Once the initial sampling sites were determined, subsequent soil cores were taken within 5 m of the initial location. The cores were sectioned to give 0–100, 100–200, 200–400, 400–600, 600–800, 800–1000, 1000–1300, 1300–1600 and 1600–1900 mm depth increments. The minimum sampling routine involved taking cores at sowing, anthesis and harvest. More intensive sampling was undertaken in 2013, but these cores were taken to a maximum depth of 1000 mm. The wet soil was stored at < 4 °C until processed. Processing consisted of weighing the total mass of soil in the section, mixing and sub-sampling for mineral N determination. The remaining soil was weighed and dried at 60 °C in a plastic bag, and then a sub-set of samples was further oven dried at 105 °C to determine the dry weight and water content. Gravimetric water contents were converted to volumetric soil water content SWC (cm^3/cm^3) using the total mass of soil and the volume of each section.

2.5. Eddy covariance measurements

The eddy covariance method was used to measure